BNL-225589-2024-JAAM

Mechanical Design of the Interaction Region Dipole B1pF for Electron Ion Collider

C. Runyan

To be published in "IEEE Transactions on Applied Superconductivity"

August 2024

Superconducting Magnet Division

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC), Basic Energy Sciences (BES)

DISCLAIMER

Mechanical Design of the Interaction Region Dipole B1pF for Electron Ion Collider

C. Runyan, K. Amm M., Anerella, J. Cozzolino, R. Gupta, H. Hocker, P. Kovach, F. Kurian, A. Marone, H. Oza, J. Schmalzle, and H. Witte

Abstract*—The Electron-Ion Collider (EIC), planned for construction at Brookhaven National Laboratory, will consist of two intersecting beams of intense electrons and high-energy protons or heavier atomic nuclei. The collider will need many demanding components, including high field superconducting magnets for the Interaction Region (IR). It has been decided that a prototype of one such magnet, the B1pF dipole, shall be built, to validate design choices common to all Rutherford cable dipole and quadrupole IR magnets. B1pF is one of several high field magnets in the interaction region whose design is based on the 15.1 mm wide NbTi cable, a cable like the one used in the main dipole coil of the Large Hadron Collider (LHC) at CERN. The current design is based on a single layer coil with an inner diameter of 300 mm and magnetic length of ~3 m which generates a magnetic field at the center of the magnet of about 3.7 T at a current of ~11 kA at design. This paper presents the mechanical design of the B1pF dipole magnet, and the R&D effort associated with the development of the prototype, including tests for successfully winding and curing coils of the needed configuration into proper structural and magnetic elements, and including a multilayer magnetic return yoke which meets field requirements while providing an initial reduced structure suitable for operational testing in an existing test facility.

***Index Terms*—Accelerator, Finite element analysis, Superconducting magnets**

I. Introduction

THE Electron-Ion Collider (EIC), to be built at Brookhaven National Laboratory (BNL), will consist of two intersecting beams of electrons and protons. The EIC will be built utilizing the existing infrastructure and accelerator facilities of the Relativistic Heavy Ion Collider (RHIC) at BNL. The EIC requires larger aperture high-field superconducting magnets in the interaction region (IR) than any current accelerator. The aperture of the EIC focusing magnets is defined by the proton's transverse momentum of 1.3 GeV/c and the neutron cone of the beam, which must make their way to the IR [1]. The B1pF collared-coil magnet was chosen as the most suitable representation of the design and manufacturing challenges inherent in the construction of the EIC IR. Collared coil magnets are a prevalent and proven design in accelerator applications, with magnets such as the RHIC DX Dipoles, the Large Hadron Collider's (LHC) dipole, the Hadron-Electron Ring Accelerator's (HERA) main dipoles, and The Tevatron's main dipoles, all employing a variation on a collared coil design [2].

A prototype of the B1pF utilizing NbTi superconducting Rutherford cable made from 28 individual 1.065 mm diameter strands, will be built and cold tested at BNL. This cable is similar to the LHC's Type 01 cable at Conseil Européen pour la Recherche Nucléaire (CERN) [3].

The B1pF is larger in size than any comparable accelerator magnet and consists of a single-layer coil with an inner diameter of 300 mm and 63 turns arranged in six conductor blocks. The coil has a magnetic length of approximately three meters, and will generate 3.7 T at a current of 11 kA. Complete magnet parameters are described elsewhere [1][4].

The B1pF prototype will not include the outer yoke, because of in-house dewar testing size restrictions. Instead, the prototype will operate at 14.2 kA to reach a comparable maximum azimuthal stress on the coil.

II. Magnet Mechanical Overview

The B1pF magnet uses a collared coil design similar to the RHIC DX dipole design [5] and primarily consists of the coils, collars, inner and outer yokes, axial support rods, and endplates as depicted in Figure 1. The prototype B1pF, depicted in Figure 2, will consist of all of the same components without the shell and outer yoke halves. Pairs of spotwelded collars are locked together during the collaring process by loading vertically to a specified prestress, then phosphor bronze keys are inserted while the vertical load is removed to minimize maximum coil overpressure during assembly. This process is done in a stepwise fashion, where vertical load is incrementally reduced, while horizontal load is incrementally increased to the keys. This permits gradual transition of load from the press to the keys, thereby developing tension in the collars around the coils without over pressuring the coils to enable key insertion. These keys and welds combine in shear to allow the collars to support the radial Lorentz forces produced by the magnet. Axial Lorentz forces are supported by stiff axial bars and end plates, with set

Submitted for review September 26, 2023

This work was supported by the U.S. Department of Energy Grant No. DE-SC0021578 and by Brookhaven Science Associates, LLC under contract No. DE-SC0012704, with the U.S. Department of Energy.

C. Runyan is with the Superconducting Magnet Division, Brookhaven National Laboratory, Upton, NY 11973-5000, USA (e-mail: crunyan@bnl.gov).
All other co-authors are also with Brookhaven National Laboratory, Upton, NY 11973-5000, USA.

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org

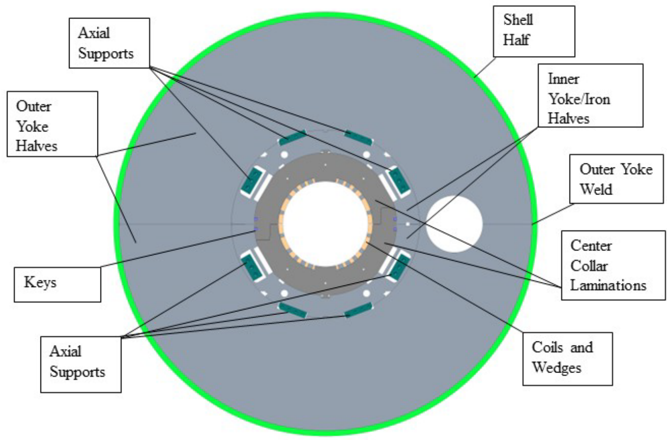

Fig. 1. B1pF Full Magnet Straight Section Cross Section

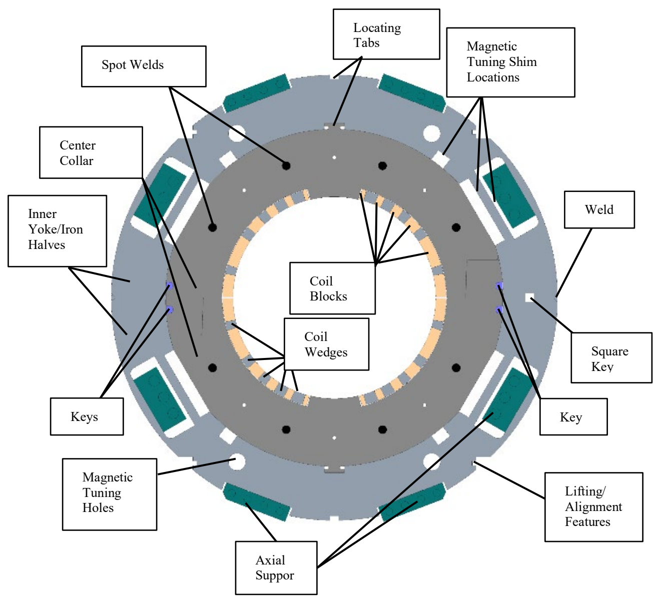

Fig. 2. B1pF Prototype Straight Section Cross Section

screws preloaded at assembly against coil end pressure plates to minimize motion during testing during coil excitation. Various parameters and dimensions for the B1pF prototype and final magnet are listed in Table I.

The collar laminations are 3 mm thick, while the inner yoke will be made up of plates that are 50 mm thick.

The inner yoke cross section includes twelve tuning shim cutouts, which will be filled with thin stacks of alternating brass and iron, which can be used to tune the uniformity of the magnet field [4].

The inner yoke is assembled and welded over the collared coil assembly using an alignment fixture. The yoke halves are located relative to one another with a square key and the assembly is welded at the midplane. Welding the yoke halves together provides enhanced radial preload on the collar assembly which deters the collars from deforming out-of-round.

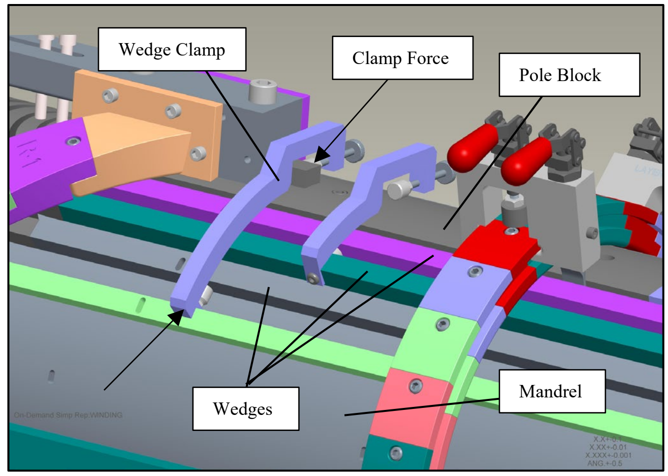

Fig. 3. Coil Winding Assembly with Specialized Wedge Clamps.

TABLE I
B1PF MAGNET PARAMETERS

Parameter	Value
Target Integral Field (T·m)	10.44
Operating Current (A)	11900
Load-line ratio at nominal field (%)	57.6
Peak field on the coil (T)	5.17
Magnetic Length (mm)	2613
Operating Temperature (K)	1.9
Coil ID (mm)	300
Collar ID (mm)	332.38
Inner Yoke ID (mm)	500
Outer Yoke ID (mm)	660.4
Outer Yoke OD (mm)	1,450
Shell Thickness (mm)	19.05
Magnet Length (mm)	3070.48
Prototype Weight (kg)	7383
Final Weight with Outer Yoke (kg)	41,816
Maximum Axial Lorentz Force (N)	533,784

III. CABLE WINDING

Based on RHIC DX coil experience, azimuthal compression from free state at winding to final size at curing requires large motion which results in gaps between parts due to excessive conductor in coil ends [5]. To combat this motion, novel tooling and methods for coil clamping and curing have been developed. Specialized wedge clamps, as depicted in Figure 3, firmly clamp the wedges against the pole block, creating a cable and wedge stack that is tightly geometrically controlled and held firmly during winding. Once the wedges are placed, they can be temporarily bolted directly to the mandrel through the azimuthal slots in the wedges to secure their position until winding is complete. If this method proves insufficient, tooling is also being fabricated to permit the B1pF prototype to be cured using a process of curing the coil in as many as four increments.

Coil end spacer geometry was designed using ROXIE [4] and independently verified with BEND software from Fermi Lab [6]. Initial coil winding tests (Figure 4) using 3D printed end spacers indicate that the real-world optimal end spacer angle is closer to vertical than indicated by ROXIE output. Further, after consultation with colleagues experienced in similar design efforts it was indicated and later proven that conductor could, without penalty, be distorted to even more vertical attitude at the peak of the coil end, which became the final design.

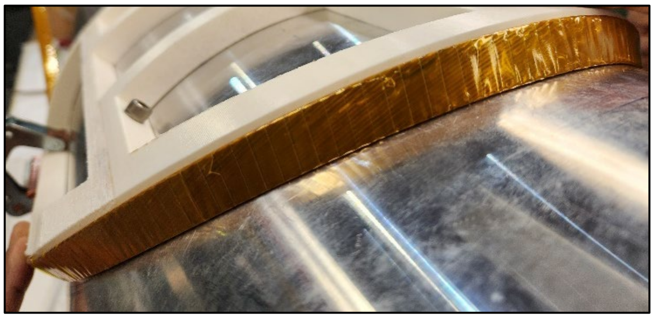

Fig. 4. Coil Winding Tests with 3D Printed End Spacers.

The coil is in an uncompressed state during winding and does not conform to end spacer geometry until the coil is cured. As depicted in Figure 5, a series of slits were added to the stainless steel end parts in order to give them a little flexibility, using a design similar to the design used in the parts for the LHC QXF coils. The flexibility allows the parts to expand to fit around the uncompressed cable when they are installed during winding and then allows the parts to return to the design shape when the coil is compressed to its final size during curing.

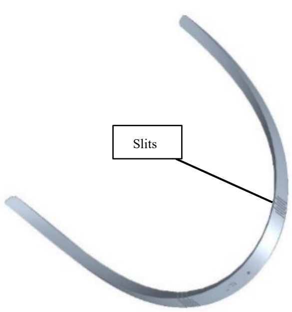

Fig. 5. 3D Printed Coil End Spacer with flexible joints.

IV. Magnet Mechanical Design And Optimization

TABLE II
B1PF MAGNET COMPONENT MATERIALS

Component	Material
Coils	NbTi
Wedges	OFHC Copper
Collars	10% Cold Reduced 21-6-9
Yokes	99.98% Pure iron
Shell, Axial Bars, End Plates	304 L Stainless Steel
Keys	Phosphor bronze

Magnetic design was performed in ROXIE and the yoke and coil designs were imported into PTC CREO for mechanical design. Finite Element Analysis (FEA) was performed in ANSYS Workbench to determine stresses, deflections, and strain in magnet components. ANSYS Maxwell 3D was employed to simulate Lorentz forces and import directly to the structural FEA. A multiphysics transient solver was necessary to capture complex interfaces between magnet components through collaring at room temperature, cooldown to 1.9 K, and coil excitation. A full accounting of magnet component materials is listed in Table II. Analyses utilized nonlinear stress-strain curves and accurate $\frac{\Delta L}{L}$ integrated thermal contraction properties at cryogenic temperatures for all materials represented. 21-6-9 high strength stainless steel was chosen for the collar material because of its high yield strength, but also because it matches closely to the $\frac{\Delta L}{L}$ integrated thermal expansion value at cryogenic temperatures of the Pure iron, to minimize collar separation from the iron at cooldown. Additionally, 21-6-9 exhibits excellent magnetic permeability properties. The collar material must be 10% cold reduced in order to increase its yield strength.

A. Parametric Design Study of Collar Key Geometry

To minimize peak coil and collar stresses, and to ensure no separation between coil and collar at the pole and maintained azimuthal compressive forces on the coil through each load step, parametric design studies of the collar key geometry were undertaken.

Initial FEA results indicated very high stresses exceeding 820 MPa in the collar keyway. Several collar key geometries were parameterized and analyzed in ANSYS structural, including varying of key spacing, key radii, number of keys, key and collar interference, key depth, and key width as shown in Figure 6. Examples of the parametric study are given in Figure 7.

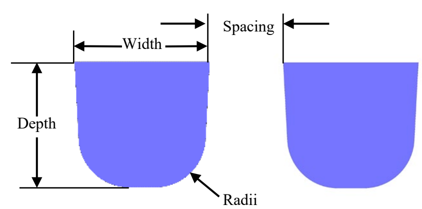

Fig. 6. Collar Key parameterized dimensions in parametric study.

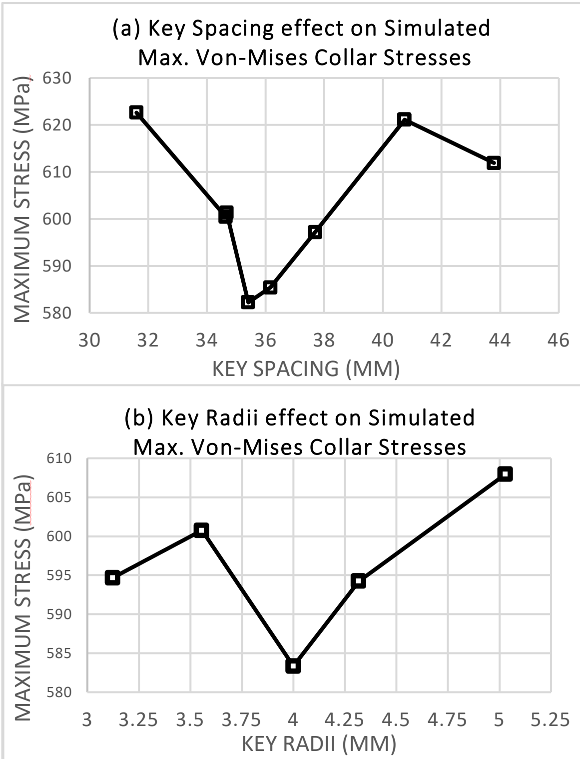

Fig. 7. Parametric Analysis of B1pF Collar Key (a) spacing and (b) radii and its effect on maximum Von-Misses Collar Stress.

The design was optimized following the design study and using the geometry that minimized stress in the collars. A three key design was also explored, but minimal improvement was observed, and it was deemed not worth the complication of an extra key. While stresses were brought within more reasonable limits, maximum stresses in the collar keyways, particularly in the lead end collars, in limited regions were still above the 620 MPa maximum stress target where the collar material will yield.

Lead end collars, which extend partially into the straight section of the magnet, are weaker than straight section collars. Lead end collars are thinner radially to make room for the exiting lead and there is additional azimuthal preload on the exiting lead, to keep the lead in compression so it does not move. As a result, the collar stresses are higher in the lead end collars, as depicted in Figure 8. The figure depicts maximum Von-Mises absolute stresses in important components at each critical assembly and use step: at collaring assembly (utilizing the collaring press), after cooldown to 4.2 K, and after coil excitation. Coil stresses at each step and in each section remain below 130 MPa, with the maximum compressive stress occurring at the midplane, and the pole block experiencing azimuthal compression throughout all steps.

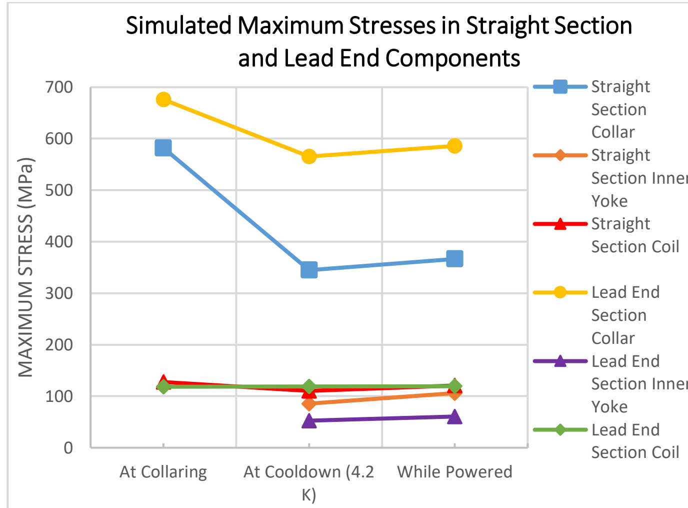

Fig. 8. Simulated Maximum Von-Mises Stresses in Straight Section and Lead End Components.

The Von Mises stress distribution for the straight section of the B1pF prototype assembly at the cold and powered step is shown in Figure 9. The collar assemblies are symmetric about the bottom plane, so are simulated using a symmetry plane.

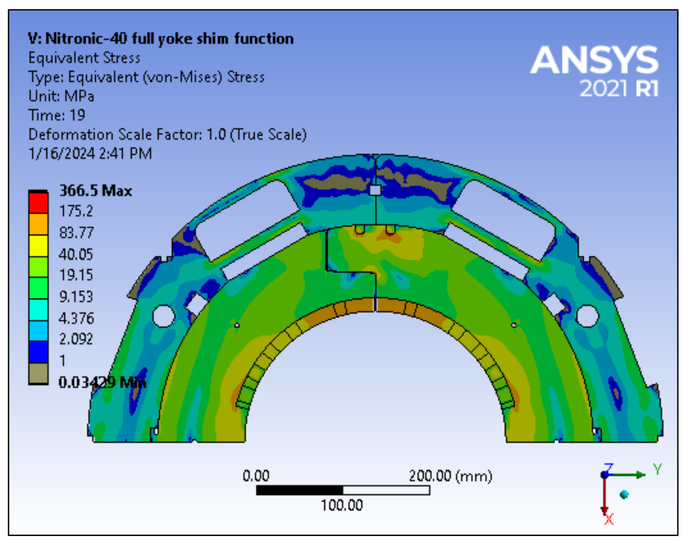

Fig. 9. Simulated Maximum Von-Mises Stresses (MPa, in log scale) in Straight Section for B1pF Prototype at Powered step. Deformation is shown at true scale.

While the lead end collar experiences stress higher than that of the yield strength of the material, the strain in this area is less than 1%, and the region over which the stress is higher than the material yield stress does not penetrate the interior of the collar.

B. Axial Support Structure

Using the helium vessel as part of the axial support system would result in unacceptable deflections and end plate thicknesses due to the large 1.5 m outer yoke diameter. A support shell around the inner yoke was considered and rejected as it would create alignment issues and interrupt flux coupling to the outer yoke. As a result, the B1pF uses eight

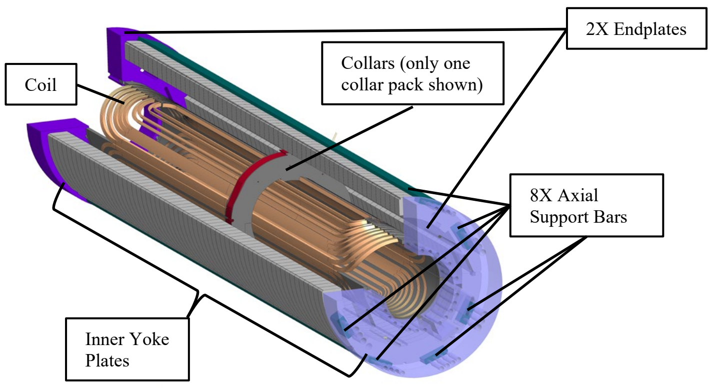

Fig. 10. B1pF Prototype 3D cutaway view

rectangular axial support bars azimuthally spaced strategically to have as little influence on the magnetic field as possible.

In this magnet, the axial Lorentz force produced by the coil are restrained by setscrews instrumented with strain gauges at the coil mean radius, near the inner radius of the end plate, which are preloaded to mitigate coil movement at cooldown. The axial support bars, made from 304 L Stainless Steel, are designed to provide enough rigidity to the endplates to counteract the axial Lorentz force of 533.8 kN per end. The axial bars are bolted on end to each endplate and bolts pretensioned to prevent movement at cooldown and excitation, as shown in Figure 10. Since the endplates are loaded by the Lorentz force at the inner radius, and they are attached to one another through the axial bars near the outer radius of the endplate, there is a significant bending force on the endplates that is reduced the closer the axial bars are located to the inner radius.

Due to the demanding forces placed on the axial bars and endplates, both endplates must be 15.2 cm thick to minimize deflections and provide sufficient margin against failure, which puts the B1pF total length close to the maximum envelope allotment. The axial bars will also serve as axial spacing for the inner yoke plates wherein each yoke plate will be fastened radially to the four axial bars via a series of ¼”-20 bolts running along the magnet in the axial direction, permitting axial contraction on cool down to be dominated by the stainless steel bars and coils.

V. Manufacturing And Tooling

To meet the project’s timeline, we have planned for the earliest possible coil winding and curing experiments by fabricating half-length test coils using readily available copper wire of proper size formed into 28 strand Rutherford cable. Various tooling fixtures for the express fabrication of the B1pF prototype have already been designed and some have been fabricated. These include a coil azimuthal measurement fixture, a modified short section collaring press, a full-size collaring press, and a modified full-size curing press, as shown in Figure 11.

The collaring press, which utilizes hydraulic cylinders to preload the collar assembly for key insertion, reuses frame and cylinders from a RHIC press and employs newly designed components to widen the work area for the larger magnet. The collaring press in the configuration shown is used for key insertion.

The short collaring press is a modification of an existing collaring press and is designed for collaring a 22.8 cm long collar test stack to demonstrate proof of concept before the prototype is built. The modification required new vertical and side hydraulic cylinders, but the new design was able to re-use most of the existing components. Existing 230 mm long collaring press will confirm coils are made to the desired size, then assembled into collars outfitted with strain gauge transducers (later to be installed in the prototype magnet). The transducers ensure coils reach required 300 K preload (and later expected coil stress after cooldown).

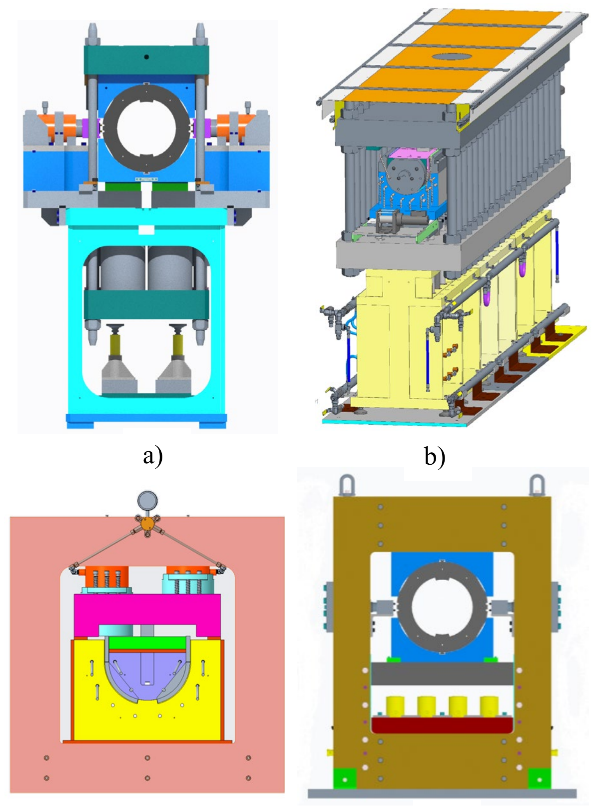

Fig. 11. Tooling Fixtures: a) Full-size Collaring Press b) Modified Curing Press c) Coil Azimuthal Measurement Fixture d) Modified Short Collaring Press.

The half-length curing press will be employed to cure a half-length proof-of-concept coil. The fixture is a repurposing of an existing collaring press and only requires power for electric heaters, new skid plates and thermal insulation to ensure the coil achieves a uniform curing temperature. The full-length curing press was previously used for RHIC and LHC coils but is being modified for compatibility with the B1pF prototype. The coil azimuthal fixture doubles as a short curing press to cure up to 230 mm long coil segments for the collaring test. This fixture will also be able to measure azimuthal coil size within 25 µm at design pressure.

A ten-stack fixture will cure and measure “10-stacks”, or vertical assemblies of ten Rutherford cable turns (and Kapton insulating layers) with alternating keystone, for early confirmation of mean assembled thickness. These coil stacks will also be used in strain gauge transducer calibrations.

VI. Conclusion

The EIC project’s large aperture, multi-bore IR magnets require innovative design and tooling to address the unique challenges associated with building such large magnets. The first of such magnets, the B1pF prototype, presents a valuable learning opportunity as the project moves forward with the design and manufacturing of all the IR magnets. Procurement of coil parts, collars, yokes, axial supports, coil lead housings, new tooling, and modifications of existing tooling are underway and will be complete in the early part of 2024, with the ultimate goal of construction and successful cold testing of the B1pF prototype magnet.

References

[1] H. Witte et al, “The Interaction Region of the Electron-Ion Collider EIC” in *IPAC2021,* Campinas,SP,Brazil, 2021, pp. 2574-2577.
[2] L. Rossi, “Manufacturing and Testing of Accelerator Superconducting Magnets”, CAS-CERN Accelerator School: Superconductivity for Accelerators, Erice, Italy, 2013,
[3] L. Rossi, “Superconducting Cable and Magnets for the Large Hadron Collider”, The 6th European Conference on Applied Superconductivity (EUCAS 2003), Sorrento Napoli, Italy, 2003.
[4] F. Kurian, “Design of B1PF- A Large Aperture Dipole Magnet for EIC”, MT28, 2023 at MT28*,* Aix-En-Provence, France, 2023, manuscript in review.
[5] J. Schmalzle et al., "RHIC DX dipole magnet construction," in IEEE Transactions on Applied Superconductivity, vol. 10, no. 1, pp. 220-223, March 2000, doi: 10.1109/77.828214.
[6] M. Yu et al., "Coil End Parts Development Using BEND and Design for MQXF by LARP," in IEEE Transactions on Applied Superconductivity, vol. 27, no. 4, pp. 1-5, June 2017, Art no. 4000105, doi: 10.1109/TASC.2016.2628863.